Coal and Shale Property Database

Final Report

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Executive Summary

The Coal-Seq III Consortium, a major government-industry collaboration effort, is managed by Advanced Resources International, Inc. It involves Oklahoma State University, Southern Illinois University and Higgs-Palmer Technologies. A series of industrial firms including BP America, the Illinois Clean Coal Institute, Sasol, BG Group and NYSERDA (among others), participate in and provide cost-share support to the Coal-Seq III Consortium.

The objectives of the Coal-Seq III Consortium are to develop and field test three advanced geochemical and geomechanical modules that would appreciably increase the accuracy of simulating the behavior of geologically sequestered CO_2 in coals and shales. These new simulation modules would enable users to couple key physical and chemical processes (e.g., coal failure and permeability enhancement; effects of matrix swelling and shrinking on permeability changes, competition of water as an adsorbed phase on coals) resulting from the injection of high-pressured CO_2. This would lead to more accurate modeling of the effects of these coupled processes on transport and storage of CO_2 in coal and shale reservoirs.

An integrated three year program of laboratory measurements, concept to code development, and field validation, by the Coal-Seq III partners, would lead to these three advanced simulation modules. A special feature of Coal-Seq III will be the development of improved simulation capability for injecting and storing CO_2 in gas shales, enabling investigators to better evaluate this large, poorly understood CO_2 storage option, particularly in the Appalachian Basin.

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1.0 Introduction

The Coal-Seq III Consortium Coal and Shale Property database was established with the purpose of compiling published and unpublished isotherm (CH_4 and CO_2), porosity and permeability data for unconventional gas plays throughout the United States and Canada (North America?). Data includes: host basin, coal or shale member, CH_4 and/or CO_2 Langmuir isotherm parameters (V_L and P_L) geologic age, location (where available), and any other salient data reported from the source.

Isotherm coverage is the main impetus of the database because permeability and porosity data are poorly reported due to lack of and difficulty constraining *in-situ* porosity and permeability from a sample. This database aims to provide a host of data from each basin to give the user a robust dataset for these various reservoirs.

2.0 Notes

Inconsistency among the data sources was a prominent matter while compiling the database:

- Some sources used metric units, while a majority favored the U.S. customary system. Metric units were converted in the database to U.S. customary system units for consistency.

- Well locations have been reported in varied formats by the data sources. These include GPS Latitude/Longitude coordinates and Public Land Rectangular Surveys (township, section and range). Additionally, not all well locations are reported or available to the public, as they may be confidential. Where no data was provided, the county or municipal boundary is given.

- An issue with isotherm data is the way in which adsorption isotherms are calculated by labs and how they are reported. The two most common methods for reporting Langmuir isotherm parameters are "as-received", and "dry, ash free" (or DAF). However, in some instances, they may be reported by different nomenclature (e.g. "in-situ", dry or moisture free). Some include both.

- Some isotherms were estimated by calculating the Langmuir parameters from graphical matching of published data where Langmuir parameters were not explicitly reported.

Each of these and any other data in the database that was manipulated in any way has been distinguished in the “notes” column in the database.

3.0 Potential Uses of Data

Adsorption Isotherms

Isotherms describe the relationship between the volumes of adsorption of a specific material (e.g. CH_4 or CO_2) onto a unit (in this case, coal or shale) over a range of pressures at a constant temperature. Two essential parameters are necessary for calculating isotherms; the Langmuir Volume (V_L) and the Langmuir Pressure (P_L). The Langmuir volume is the maximum volume of gas that can be adsorbed on to the organics for a unit of shale. It is a function of the organic richness and thermal maturity of the shale. The Langmuir pressure is a function of how readily the adsorbed gas on the organics in the shale matrix is released as a function of a finite decrease in pressure. Adsorbed gas content is calculated using the formula below (where P is original reservoir pressure).

$$GC = (V_L * P) / (P_L + P)$$

Using the Langmuir parameters, one can calculate the amount of gas able to be stored at various pressure conditions at a specific temperature. The Langmuir volume is equal to the gas volume at infinite pressure, and the Langmuir pressure is the pressure at half of the Langmuir volume.

4.0 Basin Coverage

4.1 Coal

17 coal basins are represented in the database, with a total of 226 unique isotherms (**Table 1**). This provides coverage of a majority of basins in the US, with two in Canada (**Figure 1**). **Figure 2** and **3** are high-resolution sample location maps for basins with high sample density (Stricker *et al.*, 2006; Rock Eval™ [2010, 2008], respectively).

Table 1: Coal Basins Represented and the Isotherm Quantity and Average Depth

Basin	Formation	CH_4 Isotherms (Qty)	CO_2 Isotherms (Qty)	Average Depth (feet)
Alberta Plains Basin	*Ardley*	-	8	1,107
	Drumheller	-	3	1,046
	Mannville	-	3	3,766
Appalachian Basin	*Upper Freeport*	1	1	N/A
	New River/ Lee	2	-	1,441
	Pocahontas	5	1	1,922
	Pittsburgh	1	1	714
	Freeport	1	1	1,361
Black Warrior Basin	*Upper Pottsville*	2	2	1,948
Cherokee Basin	*Senora*	1	1	772
Forest City Basin	*Senora*	1	1	780
Green River Basin	*Fort Union*	1	-	950
Gulf of Mexico Coastal Plain	*Wilcox*	1	1	4,898
	Calvert Bluff Formation	3	3	4,800
Henry Mountains Coal Field	*Ferron Coal*	4	-	1,646
Illinois Basin	*Carbondale*	58	6	973
Piceance Basin	*Williams Fork*	1	1	6,699
Powder River Basin	*Fort Union*	66	2	1,016
Raton Mesa Basin	*Vermejo*	4	-	942
San Juan Basin	*Fruitland*	15	11	3,079
Telkwa Coal Basin	*Red Rose*	3	-	425
Williston Basin	*Fort Union*	4	2	639
Wyodak Basin	*Fort Union*	1	1	N/A
Yukon Flats Basin	*Fort Yukon*	2	-	2,099

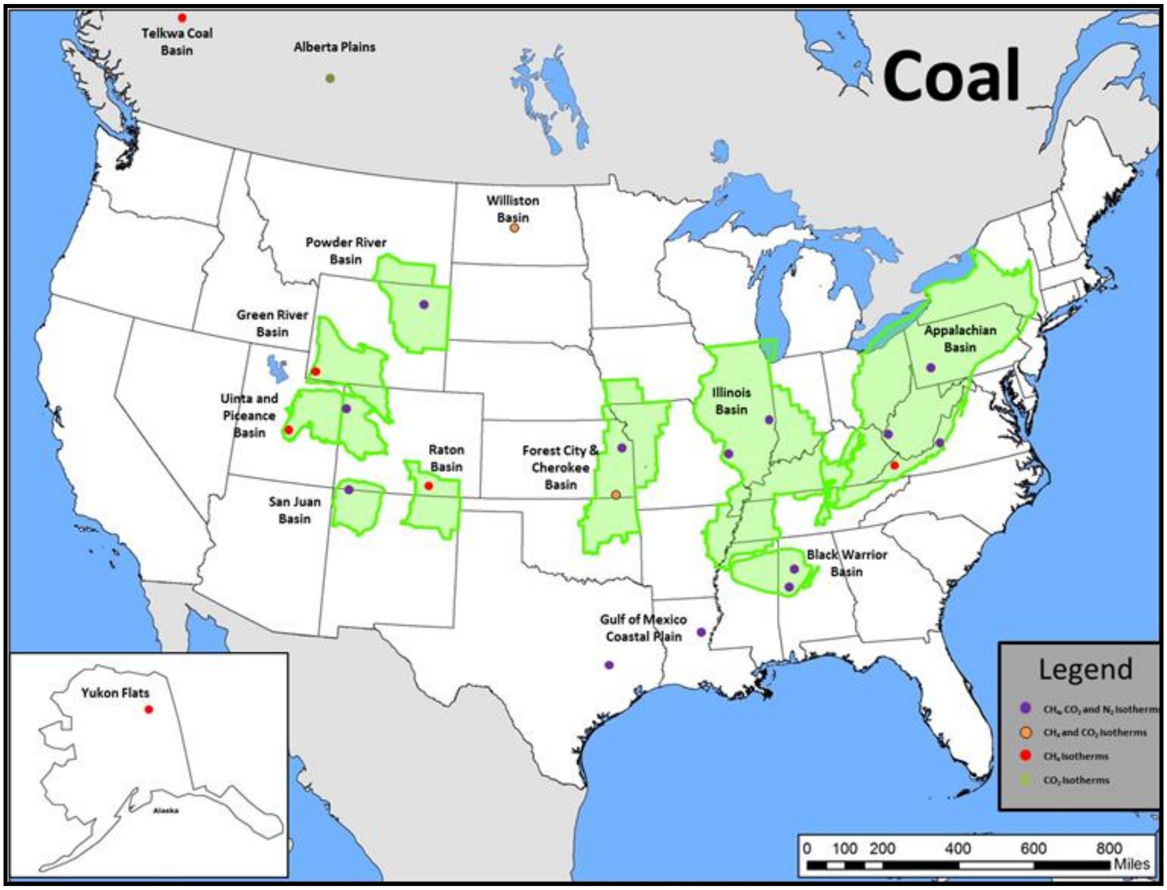

Figure 1: Map of Coal Basins and Isotherm Distribution in North America

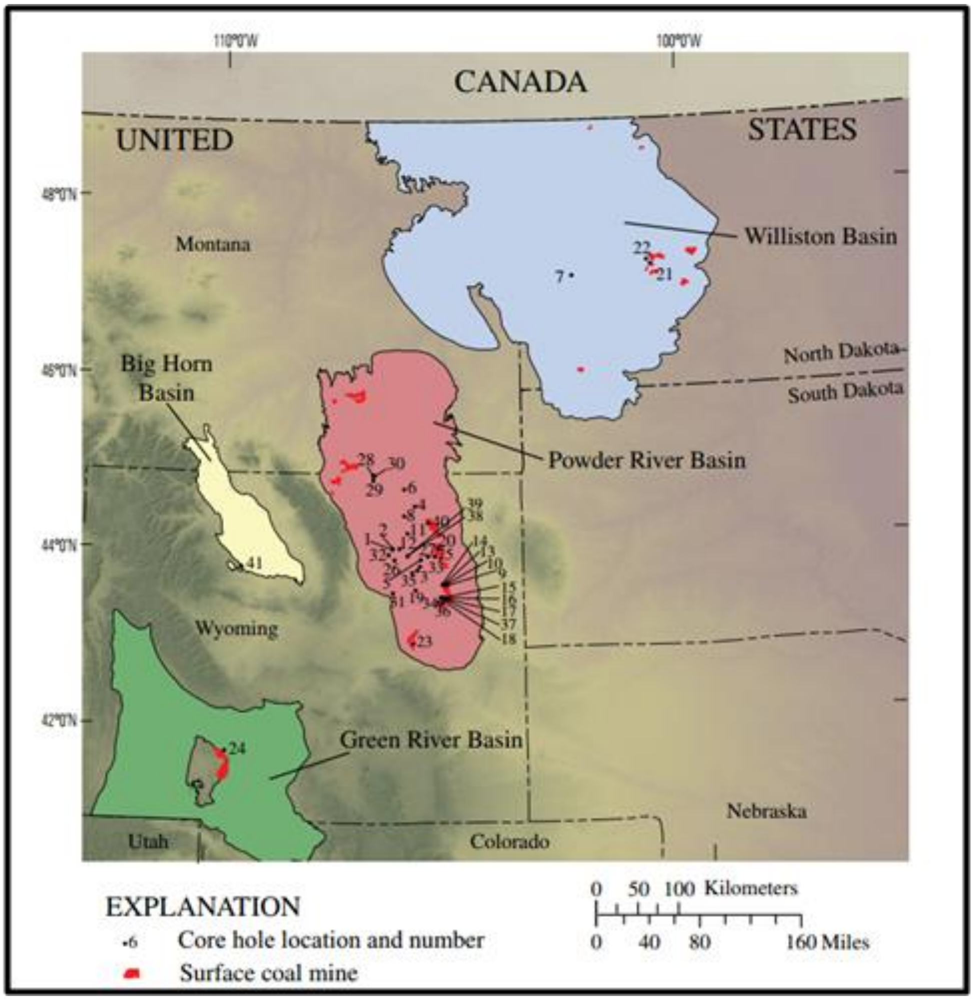

Figure 2: Location of Samples in the Powder River, Williston and Green River Basins
Map from: Stricker *et al*. (2006)

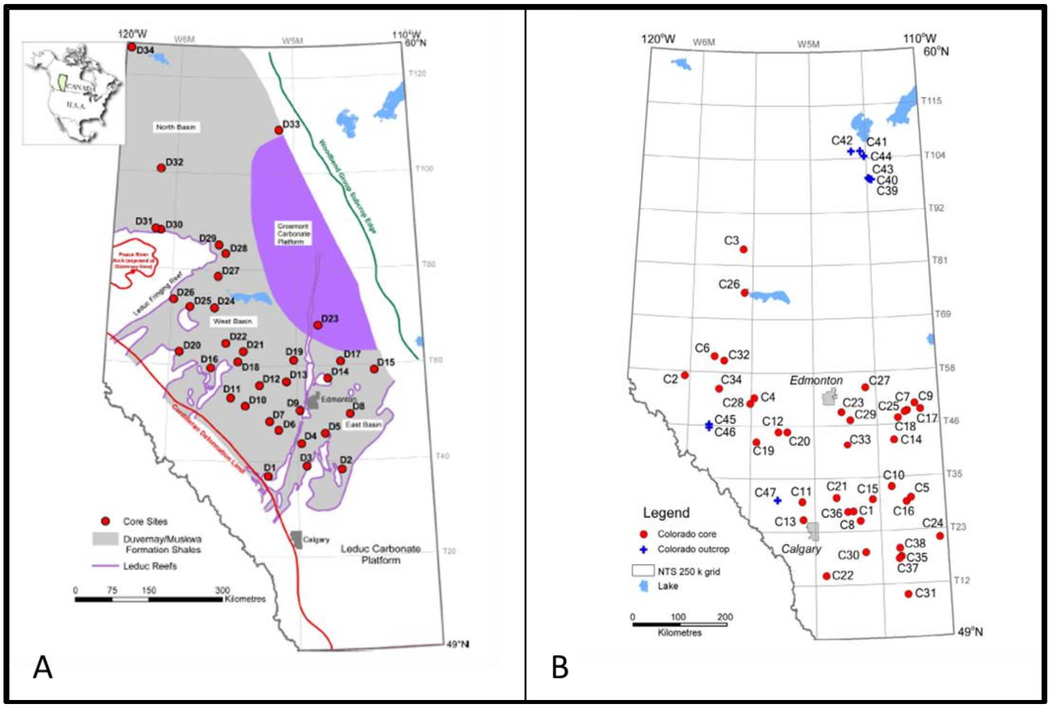

Figure 3: Map of Locations for the Duvernay and Muskwa Shale Formations (A) and the Colorado Group Shales (B) in Alberta

Maps from: **A**) Rock Eval™, 2010; and **B)** Rock Eval™, 2008

Average CH_4 isotherms for some major North American coal basins are illustrated in **Figure 4**. The plot demonstrates a wide range in average gas sorption characteristics among each basin. Illinois Basin coals are shown to average the highest gas storage capacity, while those measured in the Williston Basin rank the lowest.

Average isotherms, however, do not show the marked variation existing among isotherms in individual basins. The Powder River Basin, for example, has a wide array of isotherms among unique coal beds (**Figure 5**). A tight clustering of isotherms would indicate uniformity, which is not observed here.The coals display a relatively wide spread, with the Smith and the Roberts Coals being the most obvious outliers. This can be partly attributed to depth, which commonly plays a role in the shape of the isotherms (**Figure 6**). However, other factors such as thermal maturity and total organic content play a role in gas sorption characteristics.

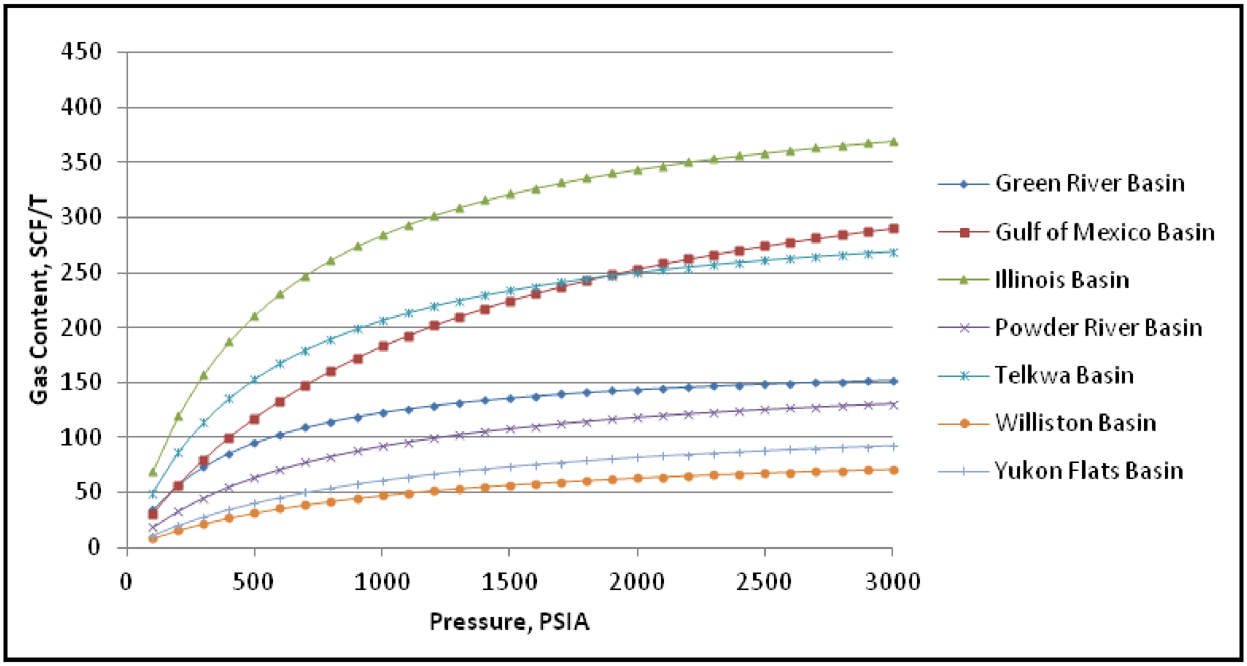

Figure 4: Average CH_4 Isotherms (as received) for North American Coal Basins

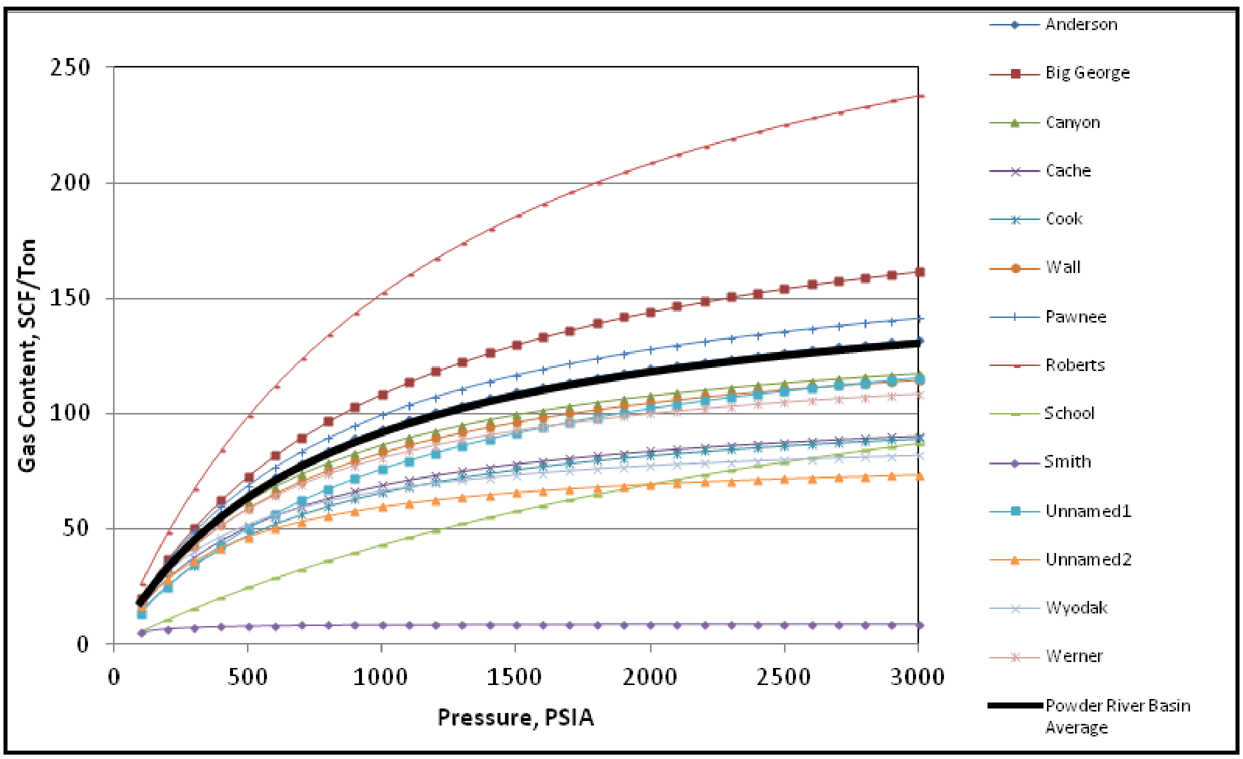

Figure 5: Variation in CH_4 Isotherms (as received) for Unique Coal Seams in the Powder River Basin

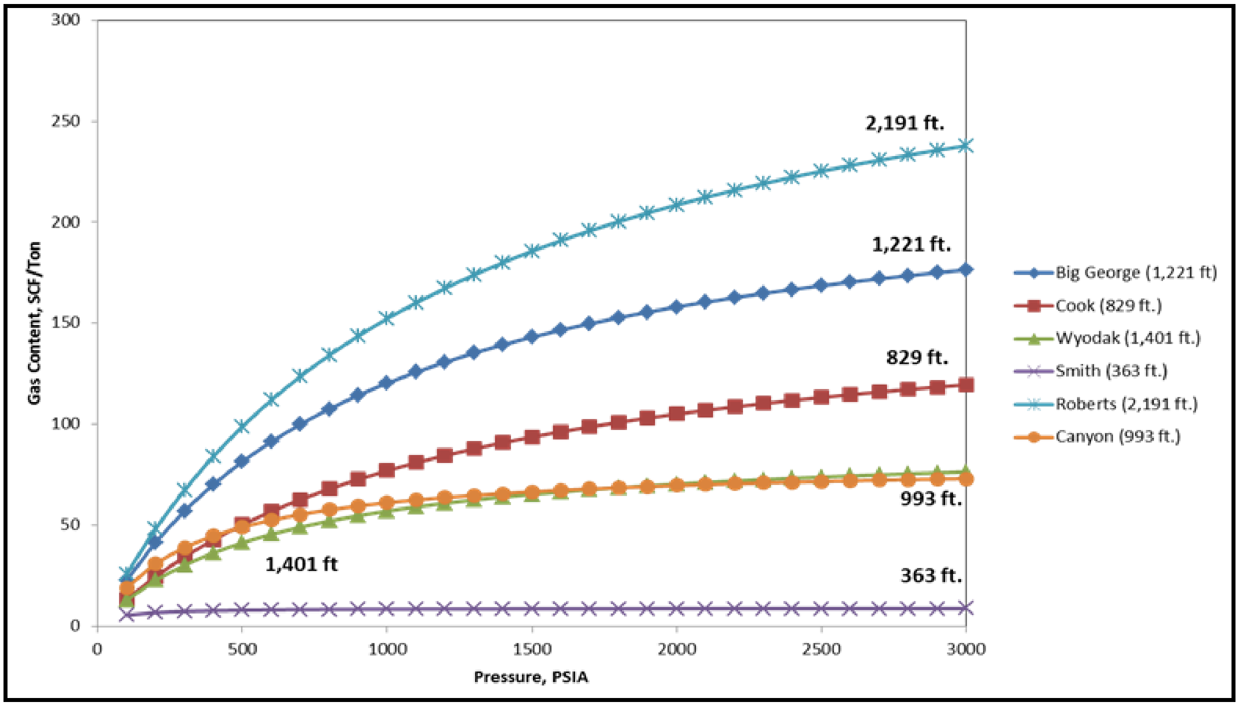

Figure 6: Variation in CH_4 Isotherms (as received) with Depth for Unique Coal Seams in the Powder River Basin.

4.2 Shale

Eleven shale basins with a combined total of 197 unique isotherms for CH_4 and CO_2 (**Table 2**) are represented in the database. Plays span the US and Canada, but coverage is most widespread in the Appalachian basin (**Figure 7**). Availability of data from burgeoning developments is poor, as data may likely be confidential. Therefore, some high-profile shale plays such as the Eagle Ford, and Fayetteville, are under-, or not represented in the database.

Analysis of CO_2 and CH_4 isotherms was conducted for several plays in the dataset. Average CO_2 isotherms for the shale basins are shown in **Figure 8**. The plot suggests that on average, the Marcellus Shale may hold the greatest amount of CO_2 relative to the other shale basins. In **Figure 9**, average CH_4 isotherms of Appalachian Basin shales are shown by state, displaying a wide variation of CH_4 capacity throughout the basin. A comparison of the CH_4 and CO_2 isotherms for a New Albany Shale in the Illinois Basin is shown in **Figure 10** to illustrate their relationship and the difference in shape. **Figure 11** is a permeability-porosity cross-plot for a Chattanooga shale well.

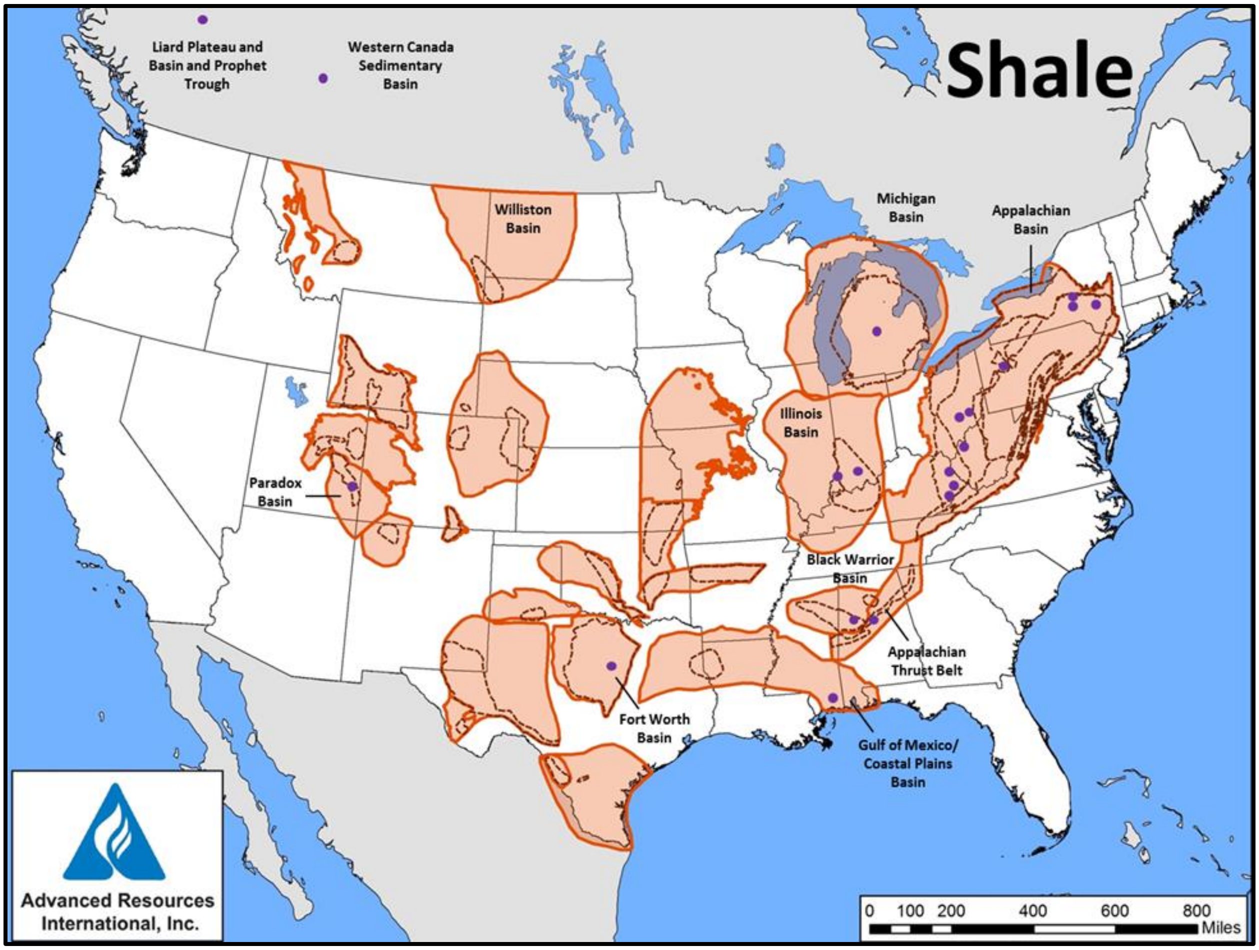

Figure 7: Map of Shale Basins and isotherm distribution in North America

Table 2: Isotherm (as-received) Quantity and Average Depth for Shale Basins

Basin	Formation	CH_4 Isotherms (Qty)	CO_2 Isotherms (Qty)	Average Depth (feet)
Appalachian Basin	*Ohio*	1	15	2,810
Appalachian Basin	*Rhinestreet and Olentangy*	1	2	4,600
Appalachian Basin	*Utica*	9	6	6,214
Appalachian Basin	*Lower Huron*	4	8	3,148
Appalachian Basin	*Marcellus*	8	2	3,520
Appalachian Thrust Belt	*Conasauga*	12	2	981
Bend Arch-Fort Worth Basin	*Barnett*	5	2	8,122
Black Warrior Basin	*Chattanooga*	10	2	9,161
Black Warrior Basin	*Devonian*	8	-	8,405
Black Warrior Basin	*Floyd*	-	2	N/A
Black Warrior Basin	*Neal*	5	-	9,020
Black Warrior Basin	*Pottsville*	-	9	1,253
Black Warrior Basin	*Pride Mtn.*	-	7	2,858
Black Warrior Basin	*Red Mtn.*	-	2	3,338
Gulf of Mexico Coastal Plain Basin	*Lower Tuscaloosa*	-	7	8,254
Gulf of Mexico Coastal Plain Basin	*Paluxy*	1	-	N/A
Illinois Basin	*New Albany*	4	5	1,755
Liard Plateau and Basin and Prophet Trough	*Besa River*	12	-	11,937
Liard Plateau and Basin and Prophet Trough	*Exshaw*	4	-	11,022
Liard Plateau and Basin and Prophet Trough	*Fort Simpson*	5	-	6,303
Liard Plateau and Basin and Prophet Trough	*Fort Simpson/ Upper Muskwa*	5	-	5,950
Liard Plateau and Basin and Prophet Trough	*Muskwa*	9	-	6,899
Liard Plateau and Basin and Prophet Trough	*Muskwa/Otter Park*	3	-	6,446
Michigan Basin	*Antrim*	2	-	N/A
Paradox Basin	*Gothic*	2	-	5,388
Western Canadian Sedimentary Basin	*Colorado Group*	12	-	6,223
Western Canadian Sedimentary Basin	*Duvernay*	4	-	8,296

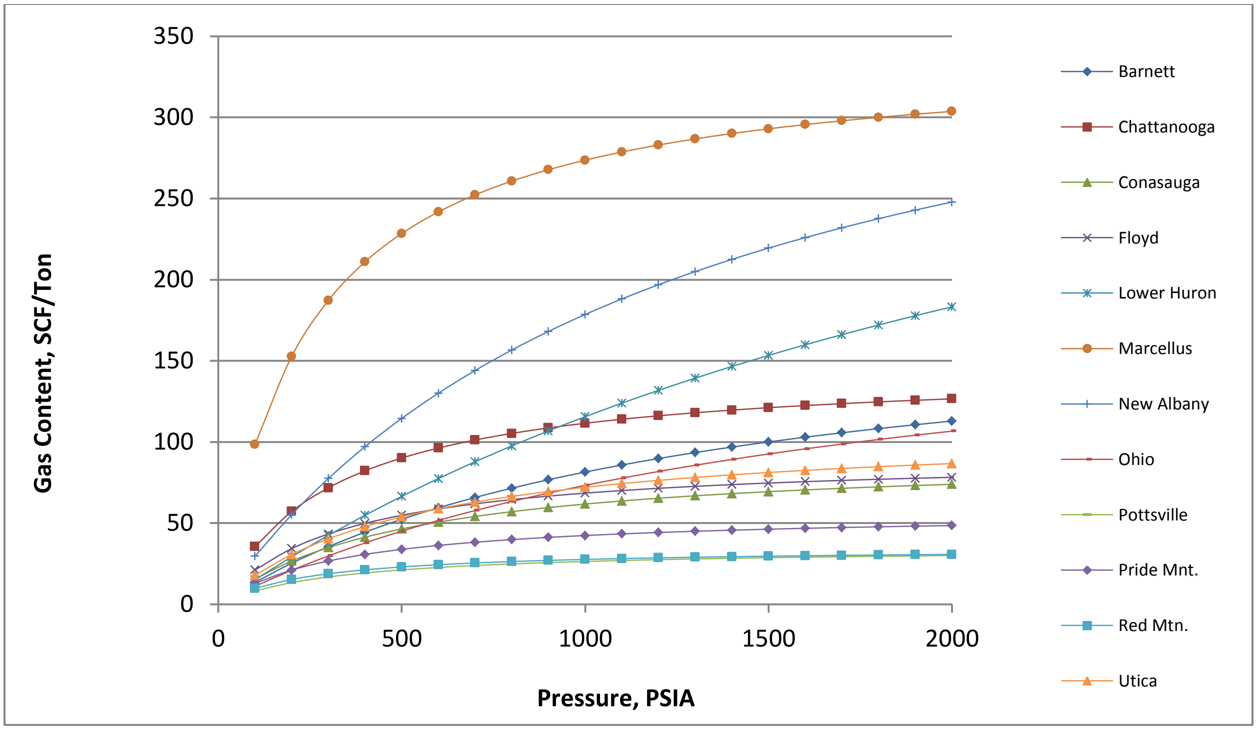

Figure 8: Average CO_2 Isotherms (as received) for North American Shale Basins

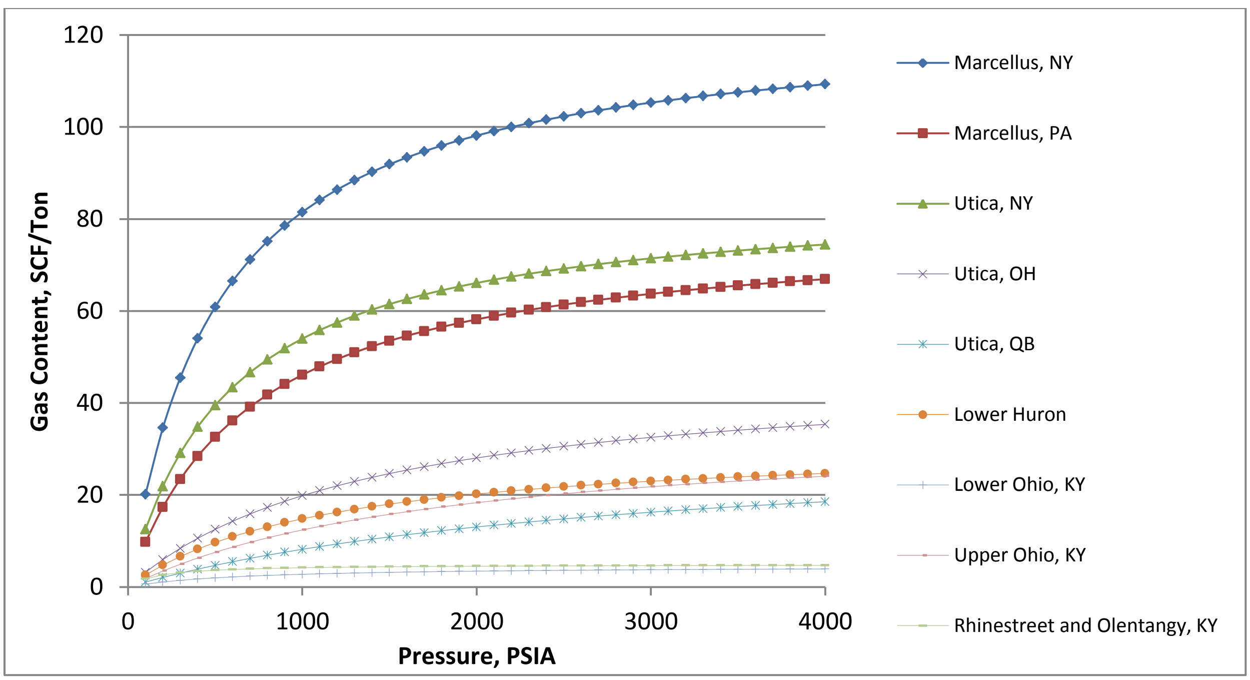

Figure 9: Average CH_4 Isotherms (as received) for Appalachian Basin Shales by State

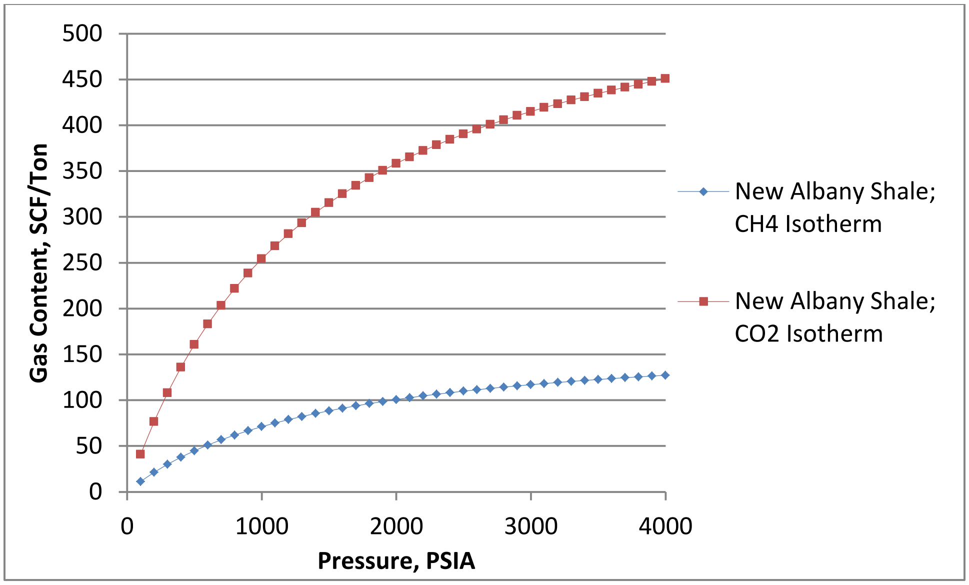

Figure 10: Comparison of CH_4 to CO_2 Isotherm for a Specific New Albany Shale Sample in the Illinois Basin (Sample: IGSID-107310-1A)

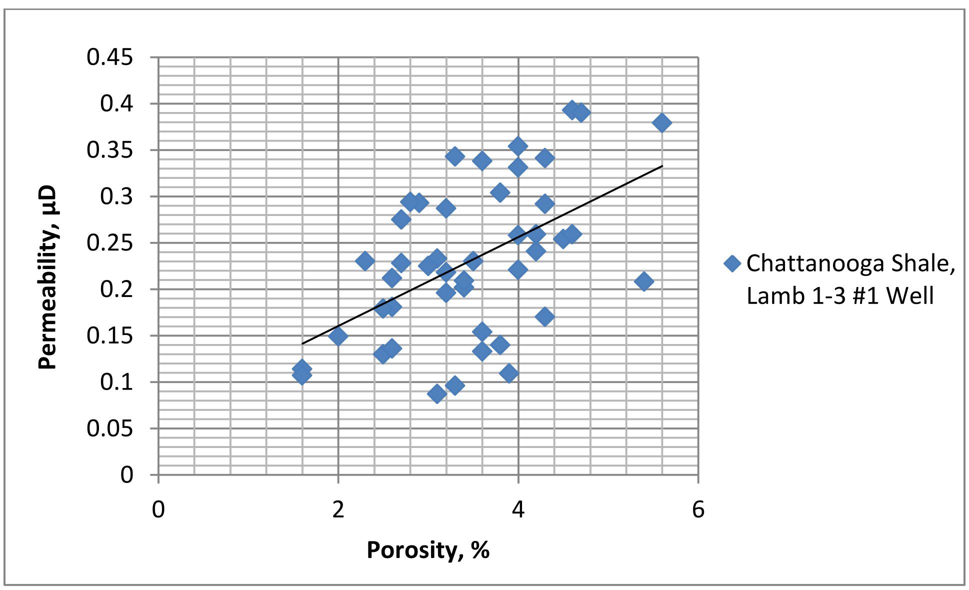

Figure 11: Permeability-Porosity Cross Plot

5.0 Summary

This database provides a broad array of isotherms and associated data over U.S. basins including a few in Canada. Isotherm data is robust, while data for porosity and permeability are underrepresented due to their difficulty to constrain.

6.0 References

1. Rock Eval™; "Total Organic Carbon and Adsorption Isotherms of the Duvernay and Muskwa Formations in Alberta: Shale Gas Data Release", ERCB/AGS Open File Report 2010-04.

2. Rock Eval™; "Total Organic Carbon, Adsorption Isotherms and Organic Petrography of the Colorado Group: Shale Gas Data Release", ERCB/AGS Open File Report 2008-11.

3. Stricker, G. D., Flores, R. M., McGarry, D. E., Stillwell, D. P., Hoppe, D. J., Stillwell, C. R., Ochs, A. M., Ellis, M. S., Osvald, K. S., Taylor, S. L., Thorvaldson, M. C., Trippi, M. H., Grose, S. D., Crockett, F. J., and Shariff, A. J.; "Gas Desorption and Adsorption Isotherm Studies of Coals in the Powder River Basin, Wyoming and Adjacent Basins in Wyoming and North Dakota", USGS, 2006.